The Luxembourg Effect - An Ionospheric Funny

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Are you located in the vicinity of a high-powered medium frequency broadcasting transmitter? Can you produce a strong signal on 160 or 80m CW? Then read on about how you may be able to observe an unusual radio propagation effect first reported more than 50 years ago.

1. Introduction

AS ANY AMATEUR WHO has used the HF bands will know, the ionosphere is a strange creature, at times well behaved and predictable, at other times violent and unco-operative. In attempting to understand the workings of the ionosphere, researchers have discovered many unexpected phenomena. The very broad field of nonlinear ionospheric physics is one area which is responsible for a number of such phenomena, and in which a lot of research is currently being pursued. One particular aspect, however, that has been known since the 1930s, is now well understood and may be of interest to other radio amateurs. "Nonlinear two-wave interaction", or "ionospheric cross-modulation" was first reported by Tellegen[1] in the international scientific journal *Nature,* in 1933. Located at Eindhoven, Holland, he noticed that if he tuned his radio receiver to Beromünster (460m), he often heard background modulation from the new high-powered broadcast station at Luxembourg (1190m). He eliminated the possibility of cross-modulation in his receiver, as well as disturbances from his town's electrical distribution system. He also noted the fact that Luxembourg is situated almost on the line directly joining Beromünster and Eindhoven (see Fig 1). Following this initial observation, he found that the Luxembourg modulation could also be heard with a number of other broadcast stations, all lying somewhat in the direction from Eindhoven to Luxembourg, but farther away than Luxembourg. His conclusion was that the phenomenon had its origin somewhere in the transmission between these stations and Eindhoven.

Evidence mounted that the "Luxembourg effect", as it became known, was due to a nonlinear effect in the ionosphere, and in 1934 Bailey and Martyn suggested[2,3] that this nonlinearity occurred in the process of absorption of the waves. The quantitative theory they developed explained the observations very well. Over the next several years, detailed investigations were made[7-13], both theoretical and experimental, and since the Second World War the phenomenon has been understood well enough to be used as a tool for investigation of the ionosphere. It is worthwhile noting here that, as with many other areas of ionospheric physics, Australian researchers figured prominently in the study of the effect. Bailey and Martyn were both Australian, as were several other key researchers in the field, notably Huxley, Hibberd, Pawsey etc. The WIA was even mentioned in at least one paper[4].

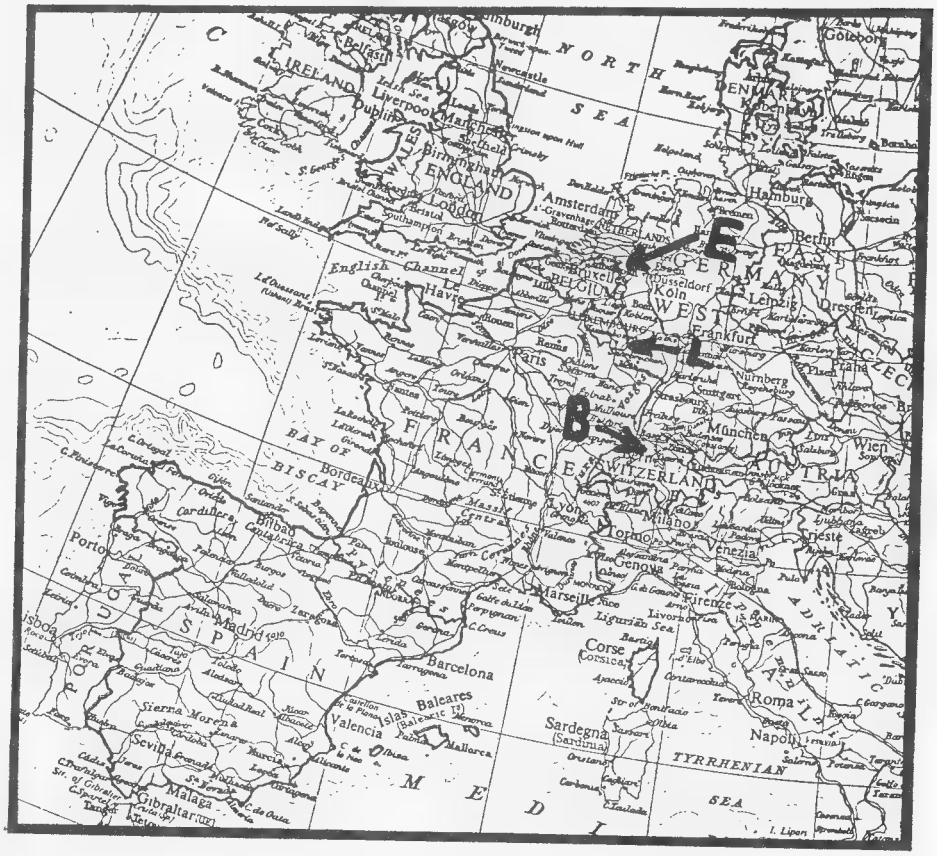

Figure 1: Location of Tellegen's initial observation

The rest of this article is organised as follows: Section 2 reviews some important concepts from ionospheric physics in this context; Section 3 contains a descriptive physical explanation of ionospheric cross-modulation; and Section 4 describes one of the ways the phenomenon has been used as a tool in ionospheric investigation. Section 3 also discusses the possibility of amateur observation of ionospheric cross-modulation.

2. Ionospheric Physics Revisited

It will be recalled that the ionosphere is "... that part of [the atmosphere[where ions and electrons are present in quantities sufficient to affect the propagation of radio waves"[5].

This ionisation occurs through the action of the sun's radiation on the various gas molecules present. The degree of ionisation depends on a number of factors, including the density of gas particles, the

temperature of the particles, intensity of the solar radiation etc. The ionisation is characterised by an *electron density profile, N(h),* which gives the electron density N as a function of height h. Fig 2 shows some idealised profiles. As can be seen, N increases with height up to about 300km. The appearance of peaks in these profiles gives rise to the usual classification of the ionosphere into the *D region* (from heights 40km to 90km), the *E region* (90km to 160km) and the *F region* (>160km).

Another parameter that is important in ionospheric physics is the *electron collision frequency, v.* This is the average rate at which free electrons collide with heavy particles (ions, molecules). This collision frequency also depends on height, but, unlike electron density, it decreases with increasing altitude. Fig 3 shows a typical electron collision frequency profile. The decrease in collision frequency with height is as one would expect, since the atmosphere becomes more rarefied at height, and so particles have fewer collisions in general.

An effect which amateurs will be familiar with (particularly if their antennas are as lousy as mine!) is the absorption of waves by the ionosphere. Some quite extensive mathematical equations describing absorption have been derived, and are beyond the scope of this article. Suffice to say that ionospheric absorption is measured by an *absorption coefficient, k,* which is essentially proportional to the electron density and the collision frequency at a particular wave frequency and height, ie

$$k \propto Nv.$$

A bit of thought shows why absorption mostly occurs in the lower regions of the ionosphere. As mentioned above, N increases with height and v decreases with height. However, v decreases faster than N increases. The product Nv, then, has a maximum which, as it turns out, occurs in the D region or lower E region.

One further concept that is needed from ionospheric physics in order to understand ionospheric cross-modulation is the idea of electron temperature. We think of the temperature of a gas as being a measure of the average kinetic energy of the particles. The faster the particles are moving, the higher the gas's temperature. So, too, with electrons in the ionosphere. We can talk about the *electron temperature,* T_e, keeping in mind that this refers in some sense to the rms speed of the electrons. The electron temperature and collision frequency are related as follows:

$$v \propto \sqrt{T_e}$$

(for collisions with molecules - the dominant case).

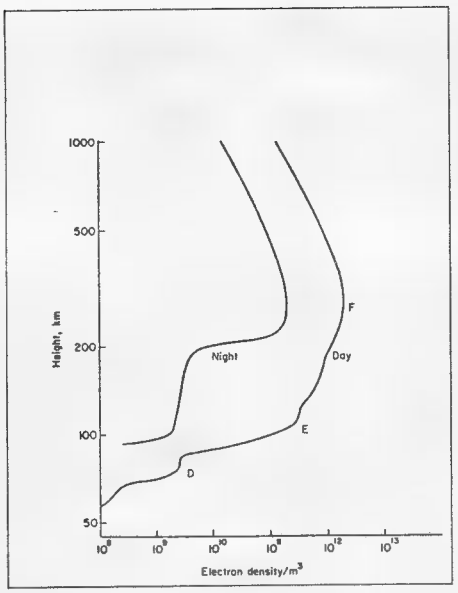

Figure 2: Idealised electron density profiles (from [16])

To summarise this section, one need only remember that radio waves are absorbed as they traverse the ionosphere, and that absorption at a particular height and wave frequency is proportional to both the electron density and the collision frequency at that height. Also, the collision frequency is proportional to the square root of the electron temperature.

3. Ionospheric Cross-Modulation

It is conventional in any discussion of ionospheric cross-modulation to speak of the "wanted wave" and the "disturbing wave". Ionospheric cross-modulation, as with receiver cross-modulation, results in the transfer of modulation from the disturbing wave to the wanted wave. In the ionospheric case, this transfer of modulation occurs as both waves pass through the same region of the ionosphere, called the "region of cross-modulation". This terminology is illustrated

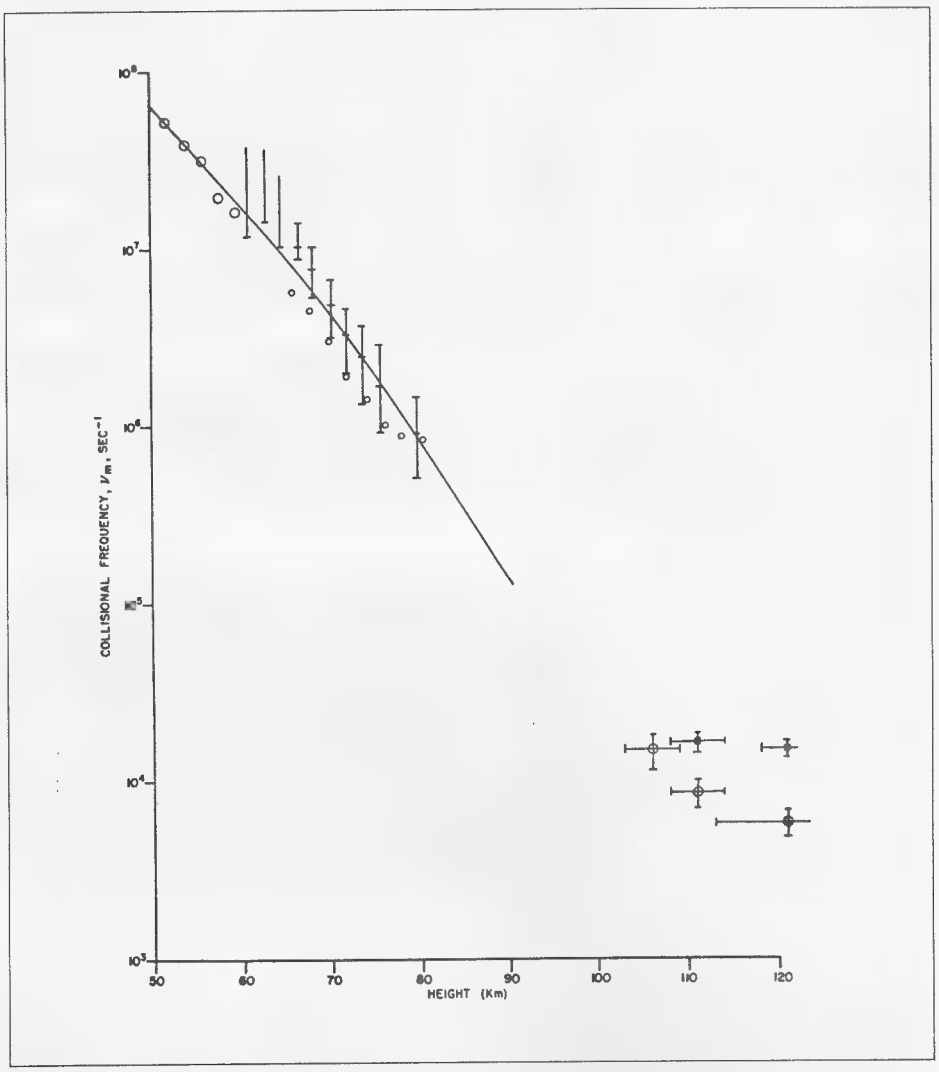

Figure 3: Electron collision frequency profile (from [15].

diagrammatically in Fig 4.

From the previous section, we know that the absorption of a wave in the ionosphere is proportional to the electron collision frequency which, in turn, is proportional to the square root of electron temperature. Suppose that the electron temperature was changed somehow. This would then change the collision frequency and the absorption coefficient; an increase in electron temperature would increase the absorption, a decrease in T_e would decrease the absorption. The strength of a wave passing through this region would decrease or increase, respectively. Now consider what would happen if a very strong RF wave could "heat" the electrons. The above argument shows that turning such a wave on would increase ionospheric absorption in the region it heats. The strength of another wave passing through the same region would be reduced. If the strong heating wave (the disturbing wave) was amplitude modulated, the electron temperature would become modulated, causing the collision frequency and absorption coefficient to become modulated. Another wave passing through the region (the wanted wave) would then also become amplitude modulated because of the varying absorption. This is the essence of ionospheric cross-modulation. It can be shown that the heating effect of a wave is given by the following equation:

$$\Delta T_e = \frac{e^2 E_0^2}{3mk\delta(\nu_0^2 + \omega^2)}$$

where

ΔT_e = increase in electron temperature, K,
e = charge on electron, $1.6 \times 10^{-19} C$,
E_0 = amplitude of disturbing wave, V/m,
m = mass of electron, $9.1 \times 10^{-31} kg$,
k = Boltzmann's constant, $1.38 \times 10^{-23} J/K$,
δ = fraction of electron's energy lost in a collision, = 2×10^{-3}
ν_0 = undisturbed electron collision frequency,
w = $2\pi f$ = angular frequency of disturbing wave, rad/s.

Table 1 lists some typical percentage increases in electron temperature for several locations in the ionosphere and several powers and frequencies of disturbing waves. From this we can see that only very high powered, medium frequency waves can significantly affect the electron temperature.

Mathematical expressions can be derived for the actual depth of cross-modulation produced on the wanted wave. It turns out that cross-modulation is produced at the modulating frequency and twice the modulating frequency of the disturbing wave, although the latter is much weaker. Rather than give the full equations for the cross-modulation depth, which can get rather messy, I will instead look at the dependence of the transferred modulation on various parameters.

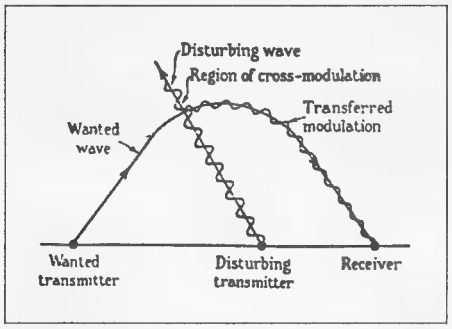

Figure 4: Nomenclature in ionospheric cross-modulation (from [14])

3.1 Dependence on Modulation Frequency

The transferred modulation obeys the following relation:

$$M \propto \frac{1}{\sqrt{(\delta\nu_0)^2 + \Omega^2}}$$

where

M = wanted wave cross-modulation depth,
δ, ν_0 = as before,
Ω = modulation frequency.

Fig 5 shows a plot of this variation. The dots on this graph show experimentally determined points. It can be seen that the theoretical curve is quite consistent with experiment. This curve also shows that the cross-modulation depth is strongest at low modulation frequencies.

3.2 Dependence on Power of Disturbing Wave

Both theory and experiment show that the depth of cross-modulation is proportional to the power of the disturbing wave.

3.3 Dependence on Modulation Depth of Disturbing Wave

Again, theory and experiment both show that the cross-modulation depth is proportional to the modulation depth of the disturbing wave.

3.4 Dependence on Frequency of Disturbing Wave

Theory predicts the dependence on disturbing wave frequency to be given by:

$$M \propto \frac{1}{\omega^2 + \nu_0^2}$$

This seems to have been borne out in practice. It is clear that cross-modulation will be more pronounced the lower the frequency of the disturbing transmitter. This is in accordance with the observation earlier that the lower the frequency of the transmitter, the better it is at heating the electrons in the ionosphere.

3.5 Dependence on Frequency of Wanted Wave

Since cross-modulation is due to nonlinear absorption, the effect will be strongest when both waves are absorbed most strongly in the same region of the ionosphere. This implies that cross-modulation will be most noticeable if the wanted wave is reflected from the lower regions of the ionosphere, ie if it is fairly low in frequency.

3.6 Dependence on Earth's Magnetic Field

The fact that the earth has a magnetic field alters the results for dependence on disturbing wave frequency somewhat. The modified form of the earlier relation is:

$$M \propto \frac{1}{(\omega - \omega_p)^2 + \nu_0^2}$$

Ionosphere	Frequency (MHz)	ΔT_e (%) 10kw	100kw	200kw	500kw	1000kw
D layer (daytime)	< 0.48	0.2	2	4	10	20
$\nu_0 = 10^7$	1.6	0.1	1	2	5	10
$T_e = 300°K$	16	0.002	0.02	0.04	0.1	0.2
$\delta = 2 \times 10^{-3}$						
h = 60km						
Lower part of E layer (night)	< 0.03	30	140	210	360	570
$\nu_0 = 7 \times 10^5$	0.16	10	80	140	270	430
$T_e = 200°K$	0.32	4	30	60	150	270
$\delta = 2 \times 10^{-3}$	0.80	0.6	6	10	30	60
h = 90km	1.6	0.2	2	3	8	20
	16	0.002	0.02	0.03	0.08	0.2
F layer	16	0.0004	0.0004	0.0008	0.002	0.004
$\nu_0 = 10^3$						
$T_e = 2000°K$						
$\delta = 10^{-4}$						
h = 300km						

Table 1: Increases in electron temperature for different powers and heights

where w_p is the so-called gyro-frequency and depends on the local value of the earth's magnetic field. Typically, the gyro-frequency would be around 1500kHz. Theory predicts that a "resonance" would occur if the disturbing wave frequency is equal to the gyro-frequency and there is some evidence that significant increases in cross-modulation depth do occur as the disturbing wave frequency passes through the gyro-frequency[4]. However, the gyro-frequency generally varies greatly with position in the ionosphere so that this gyro-resonance is not often observed.

3.7 Amateur Observation of Ionospheric Cross-Modulation

From all the above considerations, ionospheric cross-modulation is most likely to be experienced in an amateur radio context on either 160m or 80m. The received signal would have to be mostly skywave, and there would most likely be a high powered medium frequency AM broadcast station situated about halfway between one amateur station and the other. The cross-modulation would best be observed using AM, or just transmitting a carrier wave.

4. Use of Ionospheric Cross-Modulation for Ionospheric Diagnostics

This section outlines a method due originally to Fejer[6] for using ionospheric cross-modulation to determine electron densities and collision frequencies in the lower ionosphere.

Referring to Fig 6, the experimental set-up consists of two pulsed transmitters and a receiver, all at the same site. The receiver is tuned to receive the reflected pulses from the wanted transmitter. These pulses are sent with a certain repetition rate. Now consider the disturbing transmitter. As the RF pulse from this transmitter travels upwards, it heats the ionosphere. At some point it will meet up with the reflected wanted pulse. Suppose this happens at a height h_o. Then for the rest of its trip back to the receiver, the wanted pulse will be more

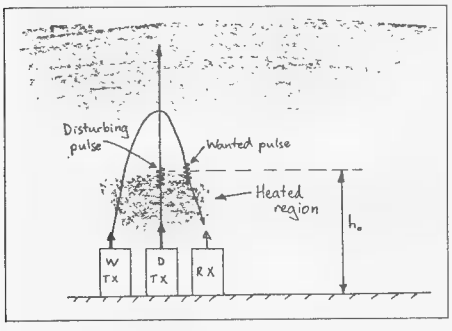

Figure 6: Fejer's experimental set-up

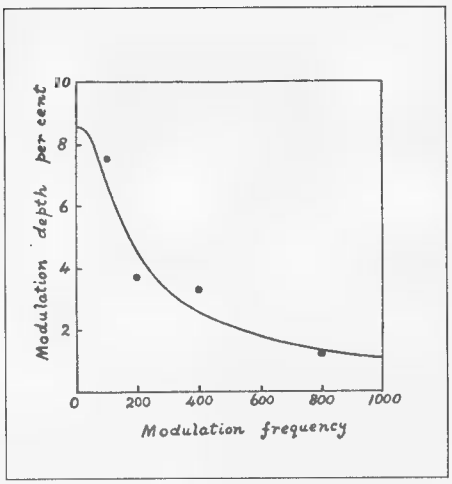

Figure 5: Variation of cross-modulation depth with modulation frequency (from [7])

strongly absorbed, since it is travelling through a heated part of the ionosphere. If the disturbing pulse is sent at a time t_0 before the arrival of the wanted pulse on the ground, then the height h_o is given by $h_o = ct_o/2$, where c is the speed of light. The repetition rate of the disturbing pulse is half of the wanted pulse, so that only every second received pulse is affected. By observing the amplitudes and phases of successive received wanted pulses, calculations can be done to find the electron density and collision frequency at height h_o. Further, by varying the time t_0 at which the disturbing pulse is transmitted, the height h_o can be varied, and so electron density profiles and collision frequency profiles can be determined. Fejer's initial results are shown in Fig 7.

5. Conclusion

The phenomenon of ionospheric cross-modulation has been described and explained. The dependence of cross-modulation depth on various parameters has been considered, and one method of using it to probe the ionosphere has been described. The possibility of amateur observation of the phenomenon has also been mentioned. Finally, I would be interested to hear from anyone who believes they have observed ionospheric cross-modulation.

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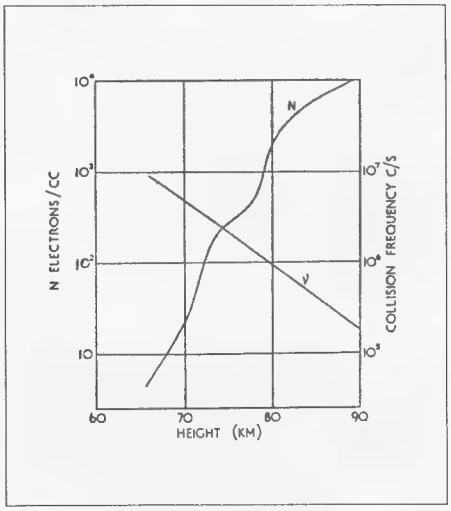

Figure 7: Fejer's results (from [6])

(The highest powered MF transmitter used in Australia is 50kW and there are 13 transmitters of this power operating, all carrying the National broadcasting service (ABC). A selection of these is: 549kHz 2CR Cumnock, 594kHz 3WV Horsham, 630kHz 4QN Townsville, 729kHz 5CL Adelaide, 774kHz 3LO Melbourne, and 558kHz 6WA Wagin. Don't forget to make allowance for the low angle of radiation from these services when looking at suitable paths for observation. Good luck! Tech Ed). **ar**